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THE SOURCE OF THE ELECTRIC FIELD IN THE NIGHTSIDE MAGNETOSPHERE

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The Source of the Electric Field
in the Nightside Magnetosphere

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Abstract

In an "open" model of the magnetosphere in which field lines from the polar cap connect to interplanetary field lines, thus carrying the interplanetary electric field into the magnetosphere, it is shown that the night side of the polar cap is nevertheless connected to closed field lines which extend into the plasma sheet. What causes the strong electric field observed on these field lines? It seems that a key factor is provided by the long narrow "windows" through which open field lines apparently leave the magnetosphere. The circuit providing electric current in the magnetopause and the plasma sheet must then extend across these windows; this drains energy from the interplanetary electric field and produces an electric potential drop across the plasma sheet. Thus the polar cap receives its electric field from interplanetary space by two pathways -- on the day side from open magnetic field lines and on the night side from closed field lines leading to the plasma sheet. The theory outlined here provides improved understanding of magnetic flux bookkeeping, of the origin of Birkeland currents and of the boundary layer of the geomagnetic tail.

Introduction

Observations of many kinds (see reviews by Cauffman and Gurnett, [1972] and by Pudovkin [1974]) indicate that an electric field E , directed approximately from dawn to dusk, extends across the magnetic polar caps of the earth. The total voltage drop across the polar cap averages about 40,000 volts and the fringing pattern of this field is mapped along closed field lines to give a dawn-to-dusk electric field in the more distant regions of the magnetosphere.

The generally accepted theory of this field is based on a suggestion by Dungey [1961] that magnetic field lines from the polar caps extend to interplanetary space. Since field lines in the interplanetary magnetic field (IMF) are "frozen" into the solar wind, such a connection between them and the polar caps cannot be a permanent one: a process is required, called magnetic merging, by which an interplanetary field line approaching earth is broken into two parts and each part becomes attached to a terrestrial field line connected to one of the polar caps. Some time after the interplanetary field line has passed the earth, this connection is broken and the two parts are reunited. An extensive literature exists about the magnetic merging process, assumed to take place at neutral points (see review by Vasyliunas [1975]).

At about the same time, Axford and Hines [1961] proposed that the magnetospheric plasma undergoes a large-scale convective flow, which also leads to a magnetospheric electric field. They recognized several possible explanations for such convection (including Dungey's) but favored a viscous-like interaction between the magnetosheath plasma

and the plasma inside the magnetosphere; this interaction extended across the magnetopause, which they viewed as a closed surface. Many of the properties of the "closed magnetospheric model" resemble those of Dungey's model, but the closed model does not explain well either the correlation between magnetospheric phenomena and the direction of the IMF or the properties of the polar cusps. In addition, a satisfactory theory of the postulated viscous-like process has not yet been advanced.

The Polar Magnetic Flux

A basic concept in theories of the magnetospheric electric field \mathbf{E} is that of the polar cap, generally defined as the polar region in which the ionospheric electric field is directed predominantly from dawn to dusk, or in different terms, where ionospheric convection is predominantly anti-sunward. The region for which this holds often ends in an abrupt boundary, also termed "reversal layer" since it marks the reversal of the convective flow from anti-sunward to sunward.

Observations indicate that the size and shape of the polar cap and the structure of its electric field all vary in time. However, we shall here assume an average model of a circular polar cap extending from magnetic latitude 78° at noon to 70° at midnight, i.e. a circle with 16° radius centered 4° nightward of the magnetic pole. In this circle the electric field will be assumed, at least as an initial approximation, to be constant in magnitude and directed from dawn to dusk (Figure 1).

The simplest "open" model of the electric field assumes that all magnetic field lines from the polar cap are open and that the fringing pattern of the electric field conducted by them from interplanetary space is responsible for an electric field on closed field lines (there exists another electric field component there, due to the earth's rotation). This view has formed the basis of some quantitative models derived by Iwasaki and Nishida [1967], Vasyliunas [1970], Volland [1973] and Stern [1974].

However, when this simple model is examined quantitatively, it becomes difficult to understand why the polar cap is as large as is observed, encompassing an appreciable amount of magnetic flux. As will be detailed below, the difficulty is two-fold : on one hand it is necessary to explain how this flux can be connected to the interplanetary magnetic field (IMF) without producing much higher voltages than are observed. On the other hand, closed field lines stretch into the magnetotail of the earth and account for an appreciable amount of terrestrial magnetic flux. If such lines are not anchored inside the polar caps, it is difficult to fit them elsewhere, while if they are connected there, an explanation for the electric field observed on them is required. This article proposes that such field lines indeed are connected inside the polar cap and that their electrical potential is conveyed to them by an electric linkage involving the magnetopause and the plasma sheet.

Consider the first point: measuring distances in the polar caps in

degrees of latitude (1 degree \approx 111 km.), the area of the polar cap, in the preceding model, is about 800 sq. degrees. In convenient units, the magnetic flux from a polar area of one square degree is about $19 \gamma R_E^2$, so that the total polar flux comes to about $15,000 \gamma R_E^2$. If all polar field lines lead to an IMF of 5γ , their cross-sectional area is about $3000 R_E^2$; assuming then the bundle of emerging polar field lines to form a circular cone, its ultimate diameter is about $60 R_E$, so that with an interplanetary electric field $-v \times B$ of about $10 \text{ kv}/R_E$ one expects a total voltage drop of about 600,000 volts across the bundle, far more than is observed in the polar caps.

To resolve the discrepancy it has been proposed [Stern, 1973a ; Morfill and Scholer, 1972] that the emerging bundle is grossly elongated and is stretched along the tail, so that its width in the direction of $v \times B$ is only about $4 R_E$ (to account for the average polar voltage drop of about 40,000 volts) while its length along the tail - in the direction of v - may reach $750 R_E$ or more. This agrees with observations of the arrival of solar flare particles at the polar caps (reviewed by Paulikas [1974]) which suggests that such particles enter the tail along a stretch of several hundred R_E .

Even if only a part of the polar cap is connected to open field lines - and even if that part is as small as the polar cusp, which has an area of about 50 sq. degrees [Hoffman, 1972 ; Shepherd and Thirkettle, 1973] - the preceding argument suggests that the open polar flux makes its exit from the magnetosphere along elongated "windows", the length of which considerably exceeds their width, which remains around $4 R_E$. These "windows" (Figure 2) can be expected to shift their position to face,

as much as possible, the direction of the interplanetary magnetic field: the entry of interplanetary field lines is then much more direct for a southward IMF than for a northward IMF and this might contribute to enhanced magnetic activity in the former case.

If these "windows" and the field lines threading them define the boundary layer recently observed [Hones et al., 1972; Akasofu et al. 1973 ; Rosenbauer et al., 1975 ; Hardy et al., 1975] then shifts in their position should be reflected in a corresponding shift of the boundary layer. In particular, the quadrant in which the boundary layer is observed should be correlated with the sector structure of the IMF in the following way:

North dawn, South dusk - for "away" sectors

North dusk, South dawn - for "toward" sectors.

Three events listed by Akasofu et al. [1973], occurring on September 28, July 24 and October 9, 1969, all agree with the above rule and correspond to "toward" sectors [Friis-Christensen et al., 1971] but a more complete analysis is highly desirable.

Thus the notion that all field lines in the polar cap are open requires them to make their exit in a rather distorted fashion. Additional arguments will now be presented to show that a large fraction of these field lines - perhaps close to one half of the magnetic flux involved - are actually closed.

Closed Polar Field Lines

When models of the geomagnetic field are devised to fit observations from space, the polar cap boundary generally falls around $L = 10$, which means that field lines leading to the geomagnetic tail are anchored on the night side of the polar cap. However, magnetic field observations in the tail [Behannon, 1970 ; Fairfield, 1968] indicate that the magnetic component B_z orthogonal to the plasma sheet is directed predominantly northwards [table on p. 751, Behannon, 1970] , suggesting that closed field lines extend at least to $70 R_E$.

Assuming that the reported average values of B_z can be taken as averages for the full $40 R_E$ width of the tail, the closed magnetic flux associated with the tail is appreciable. Akasofu et al. [1973] mapped the field onto a surface tangential to the Vela orbit at $18.5 R_E$ (figure 11 there) and find that field lines reaching the tail midplane at $18.5 R_E$ are anchored along a line extending from magnetic latitude 73° at midnight to 76° in the early and late day hours (Figure 3). One can estimate at least a lower bound to the closed flux poleward from this line from the data of Behannon [1970] , giving the averages of B_z between 20 and $70 R_E$ in the tail. Using these data one finds that the closed magnetic flux in the tail between 20 and $70 R_E$ amounts to $3000 \gamma R_E^2$, corresponding to a polar area of about 160 square degrees.

An interesting question in this connection is whether the closed magnetic flux in the geomagnetic tail can be identified with the flux

threading the plasma sheet. In figure 3 - following Lassen [1974] - we have indicated the line from which field lines extend to the boundary of the plasma sheet, as observed in Vela orbit. The magnetic flux through the area between the two curves drawn (i.e. through the northern half of the plasma sheet cross-section at Vela orbit) is about $5000 \gamma R_E^2$. As was noted above, observations of B_z suggest that 60 % of this flux closes within the lunar orbit; if the tail continues for another $200 R_E$ with an average B_z of 0.25γ (half its value at $70 R_E$) then the rest of the flux is also accounted for. In view of observations of solar proton access [Paulikas, 1974] this possibility seems to be quite plausible, in which case the plasma sheet indeed defines the bundle of closed polar field lines.

It should be noted here that on most of the closed field lines in the tail the plasma population does not extend all the way to the earth's vicinity. The particles observed by Gurnett and Frank [1973] above the polar ionosphere and identified by them as "the plasma sheet" come from the inner edge of the sheet and probably include cases where this edge has been convected an appreciable distance earthward. In contrast, most of the closed magnetic flux discussed in this section impinges a considerable distance poleward from the feature observed by Gurnett and Frank.

The Nightside Electric Field

From the preceding it appears that a considerable fraction of the polar cap - probably close to one half of its area - is connected to closed field lines. If so, what is the source of the electric field observed in this region?

One possibility is the following. If the noon side of the polar cap (the cusp region) and its middle portion receive their electric field from interplanetary space along open field lines, then the ionospheric current system produced by this field will extend some distance beyond the region of open field lines and will create there a "fringing" electric field.

In the present case, however, the electric field on closed field lines is far too strong and too extended to be explained by fringing effects. Furthermore (as will be explained later) the ionospheric current system related to Birkeland currents also seems to be associated with closed field lines, yet this system requires a "stronger" source than what fringing fields can provide.

It thus seems likely that some "strong" mechanism maintains the electric field throughout the polar cap, although the field outside the reversal boundary indeed seems to be of the "fringing" type.

To understand this mechanism in the case of closed field lines in the polar cap, consider Figure 4, which schematically shows a cross-section

of the tail, viewed from earth (see also Figure 10 of Stern [1973a]). The broad arrows trace the current flowing across the plasma sheet and returning along the magnetopause and as shown in the figure, the fact that the magnetopause is interrupted by the "windows" of open flux inserts an e.m.f. of about 40,000 volts in each half of this circuit.

By arguments which will be given below, most of this voltage will appear across the plasma sheet - e.g. between points A' and B' in Figure 2 . Because of the high conductivity parallel to the magnetic field, this same voltage will also appear between points A" and B" on the night side of the polar cap (Figure 2) , providing a source for the electric field observed in that region.

In order to justify the assumption that most of the voltage appears across the plasma sheet one must distinguish the various modes which carry the current of Figure 4 through different parts of the circuit. Three different modes exist - in the window region, in the magnetopause and across the plasma sheet.

The window region and the field lines reaching through it are the source of the magnetospheric electric field and the energy required to maintain this field is ultimately extracted from the kinetic energy of solar wind plasma attached to these field lines. Details of this process - and in particular, of the polarization current which carries the circuit flow across the window - are given in the appendix of an article by Stern [1973a] .

Assuming the magnetopause to be a tangential discontinuity, it turns out that the electric current associated with it (apart from the magnetization current associated with the sharp drop in plasma density which, however, does not contribute to the current flowing into and out of the plasma sheet) is carried by trapped particles confined to the region of discontinuity [Alpers, 1969 ; Stern 1973b, 1975b] . If a potential difference exists along the path of this current, the trapped particles will be accelerated and in doing so will diminish the potential difference. In intuitive terms, the magnetopause can be viewed as having a very low impedance for current flow in the direction which it allows.

In the same analogy, the plasma sheet can be regarded as a high-impedance conductor: it is able to carry an appreciable current only by virtue of its great thickness. Particles move across the plasma sheet by means of a rather slow guiding center drift mode [Stern and Palmaresso, 1975] : an electric field across the sheet, to lowest order, has no effect on the total current and therefore will not tend to be shorted out by the sheet. Hence most of the voltage in the circuit will probably develop across the plasma sheet, as has been assumed.

Birkeland Currents

The over-all result of the mechanism described earlier is that, as observed, a dawn-to-dusk potential difference of about 40,000 volts exists across the polar cap. On the day side this comes from open magnetic field lines leading into the magnetosheath, while on the night side it comes from closed lines connected to the plasma sheet, in the manner described earlier.

Particles in the plasma sheet will be convected earthwards by the electric field and will also be accelerated by E as the magnetic drift slowly carries them across the plasma sheet: their energy gain can be estimated from conservation of adiabatic invariants [Stern and Palma-desso, 1975]. Observations seem to confirm this convective process: while Bame et al. [1967] find that at Vela orbit proton energy peaks between 2 and 5 kev, Hills and Hardy [1975] give the corresponding range at lunar distances as 250-500 ev. The ratio between these two energy ranges approximates the ratio of average B_z at these two locations, which is what one would expect in the convection of particles with 90° pitch angle.

In addition to the field in the tail, a "fringing" electric field, due to conduction in the ionosphere, will extend beyond the boundaries of the polar cap (Figure 1). This will produce an electric field on magnetic field lines closing within $10 R_E$ or less: mapped into the equatorial plane this field will also point roughly from dawn to dusk and it will convect charged particles from the night side towards the day side [Schield et al., 1969; Wolf, 1970; Chen, 1970; Stern, 1975a].

Particles convected in this manner tend to undergo considerable energization. For instance, equatorial particles which conserve the magnetic moment increase their energy in proportion to the ambient magnetic field, so that a particle penetrating from $L = 8$ to $L = 4$ increases its energy about eightfold. For non-equatorial particles the ratio is smaller, but still considerable. It is instructive to examine how the electric field supplies this energy.

For very low energies both electrons and protons tend to move together with the electric drift velocity $E \times B/B^2$ which ties them to their initial equipotential surface. A negligible amount of charge separation is produced and the perturbation of the electric field therefore is also negligible. On the other hand, since the energy gain is proportional to the initial energy of the convected particles, the energy drain on the electric field is also negligible.

When the initial particle energy is around 1 kev the energy drain may no longer be considered small, but now magnetic drifts separate electrons from protons. Protons drift to the dusk side, electrons to the dawn side, and this charge separation creates a secondary electric field which (in conformity with Le Chatelier's principle) opposes the primary one.

What happens next depends on whether the primary source of E is "strong" and can supply the required energy with ease, or is "weak" and cannot. With a weak field source the charge accumulation will gradually "shut the field off" in the convection region and both convection and energization will be greatly reduced. A strong field ^{source,} on the other hand, will prevent charges from accumulating: to accomplish this, currents will flow between the ionosphere (where E originates, as far as closed field lines are concerned) and the charge separation region. (At still higher energies, magnetic drifts dominate the motion and do not allow particles to convect inwards and be energized).

Observations suggest that both situations occur to a certain extent. On one hand, the rapid fall-off of E outside the polar cap boundary [Heppner, 1972 ; Volland, 1973 ; Stern, 1974, 1975a] suggests that there exists an appreciable amount of "shielding" of E by space charges.

On the other hand, neutralizing currents have been observed directly [Zmuda and Armstrong, 1974] and indirectly [Sugiura, 1976] and have also been postulated by Schield et al. [1969]. On the dawn side they flow from the plasma sheet (which is the main source of E for the night side) to the polar ionosphere, then within the ionosphere to a lower latitude corresponding to field lines on which an excess of electrons has accumulated and finally outwards along field lines to regions of excess negative charge. On the dusk side all directions are reversed since the space charge there is positive (Figure 5).

The observations of Zmuda and Armstrong [1974] make it clear that the neutralizing current originates on field lines classified as closed in Figure 3. Observations suggest that this current pattern is enhanced during substorms, with the auroral electrojet representing the associated Hall current in the ionosphere: if the electric field were to originate on "open" field lines as shown in Figure 3, then the electrojet would cover a much wider range in latitude than is observed. The necessity for closing the current loop of the Hall current will somewhat complicate the picture developed here, but this added factor is not included in the simple model which has been presented.

Summary

The "open magnetosphere" model requires magnetic field lines from the polar caps (defined here as regions of anti-sunward convection) to connect to the interplanetary magnetic field and to conduct an electric field from interplanetary space to the polar ionosphere. By examining the magnetic flux involved it is concluded here that probably only slightly more than half of the magnetic flux in the polar caps belongs to open field lines and that such field lines enter or leave the magnetosphere through narrow elongated "windows" stretching along the tail. These "window" regions may be identified with the tail's boundary region and ought to shift their position with changes in the interplanetary magnetic field, in particular when there occurs a change of interplanetary magnetic sector.

Much of the night side of the polar cap is on closed field lines, which seem to be the same lines as are observed to thread the plasma sheet at $18.5 R_E$. These field lines also carry an electric field. From various observations - e.g. from the system of Firkeland currents which involves this region - it appears that the source of the nightside electric field is "strong", i.e. a low-impedance source capable of supplying appreciable amounts of energy. This source is identified as an alternative pathway connecting the "windows" through the magnetopause to the plasma sheet. Reasons are presented suggesting that almost all the voltage existing across the "windows" will also appear across the plasma sheet, from which it is conveyed along closed field lines to the nightside polar ionosphere.

A c k n o w l e d g m e n t s

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Some of the ideas in this work, like so much of magnetospheric physics, trace their beginning to an informal conversation with Neil Brice. This work is dedicated to his memory.

C a p t i o n s t o F i g u r e s

Figure 1 - Schematic view of electrical equipotentials in the polar cap: the potential of the dawn edge is about 40,000 volts higher than that of the dusk edge.

Figure 2 - Schematic view of the 3-dimensional configuration of the open magnetosphere, including the "windows". The interplanetary magnetic field, in solar magnetospheric coordinates, has positive values of B_z and B_y and the points A and B on opposite sides of the northern "window" have a potential difference of about 40,000 volts. Due to the high conductivity of the magnetopause about the same voltage appears between A' and B' while conduction along field lines conveys these potentials to points A" and B" in the nightside polar ionosphere.

Figure 3 - Boundary lines in the polar cap used in identifying regions of open and closed field lines.

Figure 4 - A cross-section of the magnetospheric tail, viewed from earth and tracing the circuit of the plasma sheet current flow.

Figure 5 - A schematic view of the electric circuit associated with Birkeland currents (compare to Figure 2).

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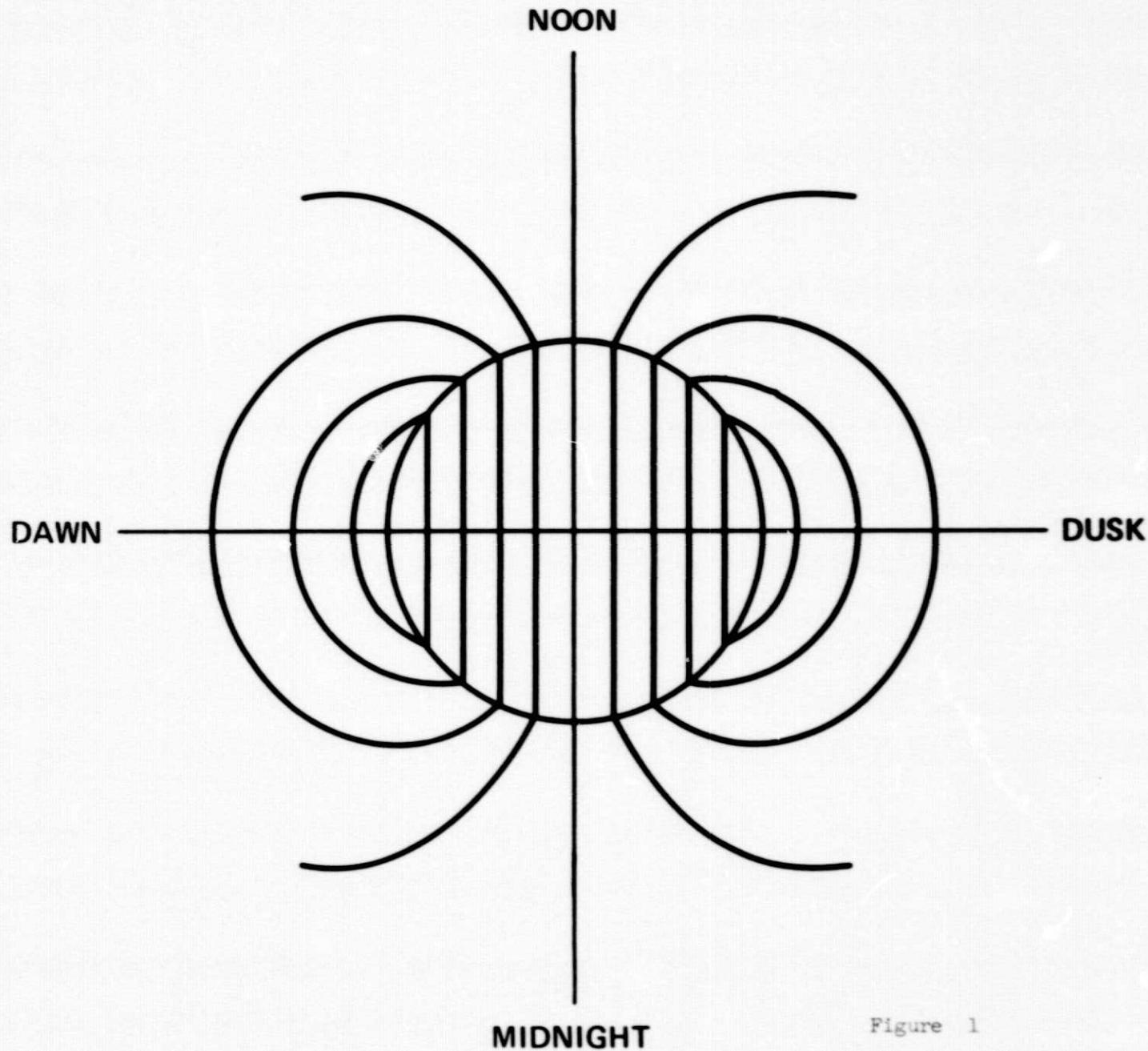


Figure 1

GENERATOR OF INTERPLANETARY ELECTRIC FIELD

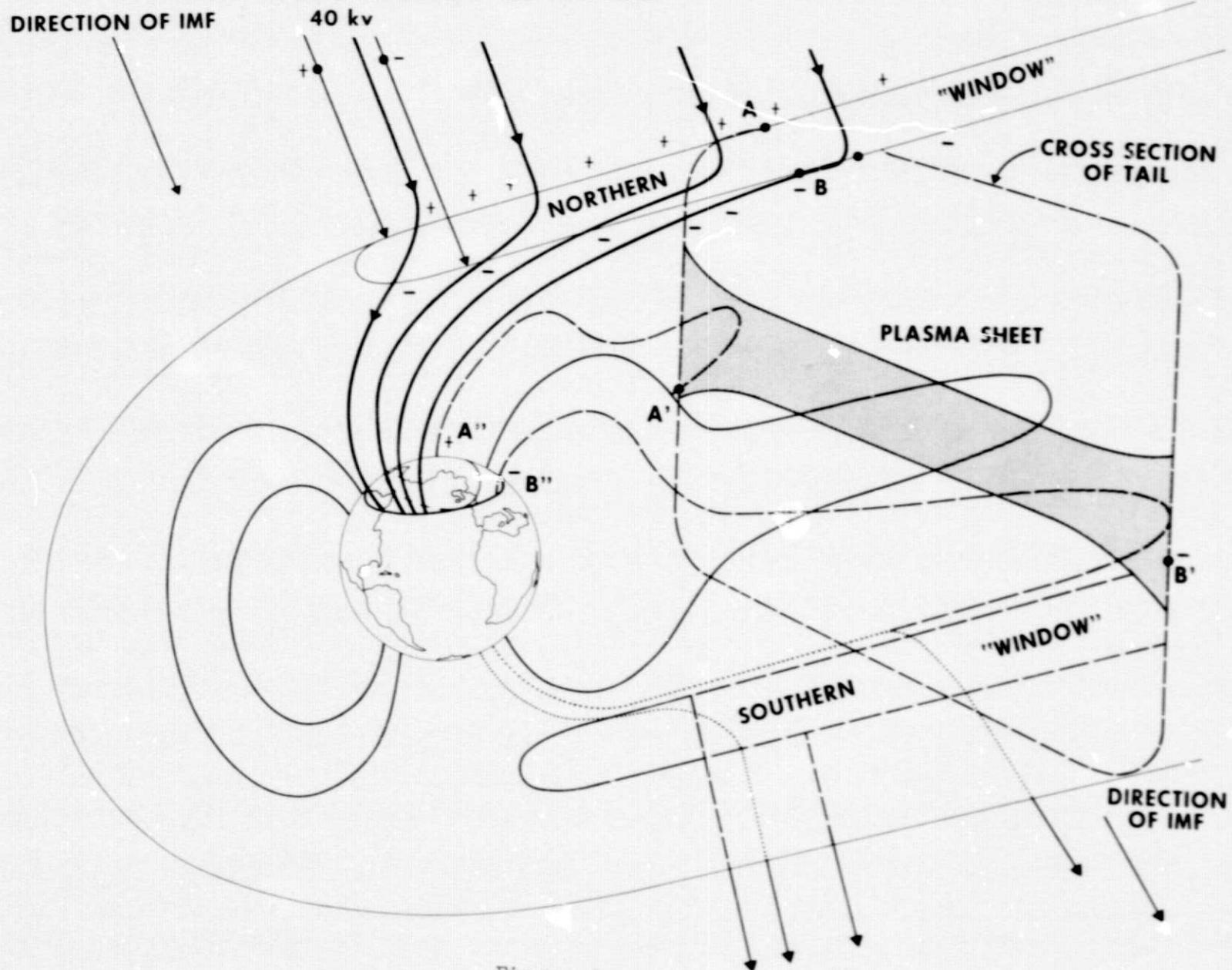
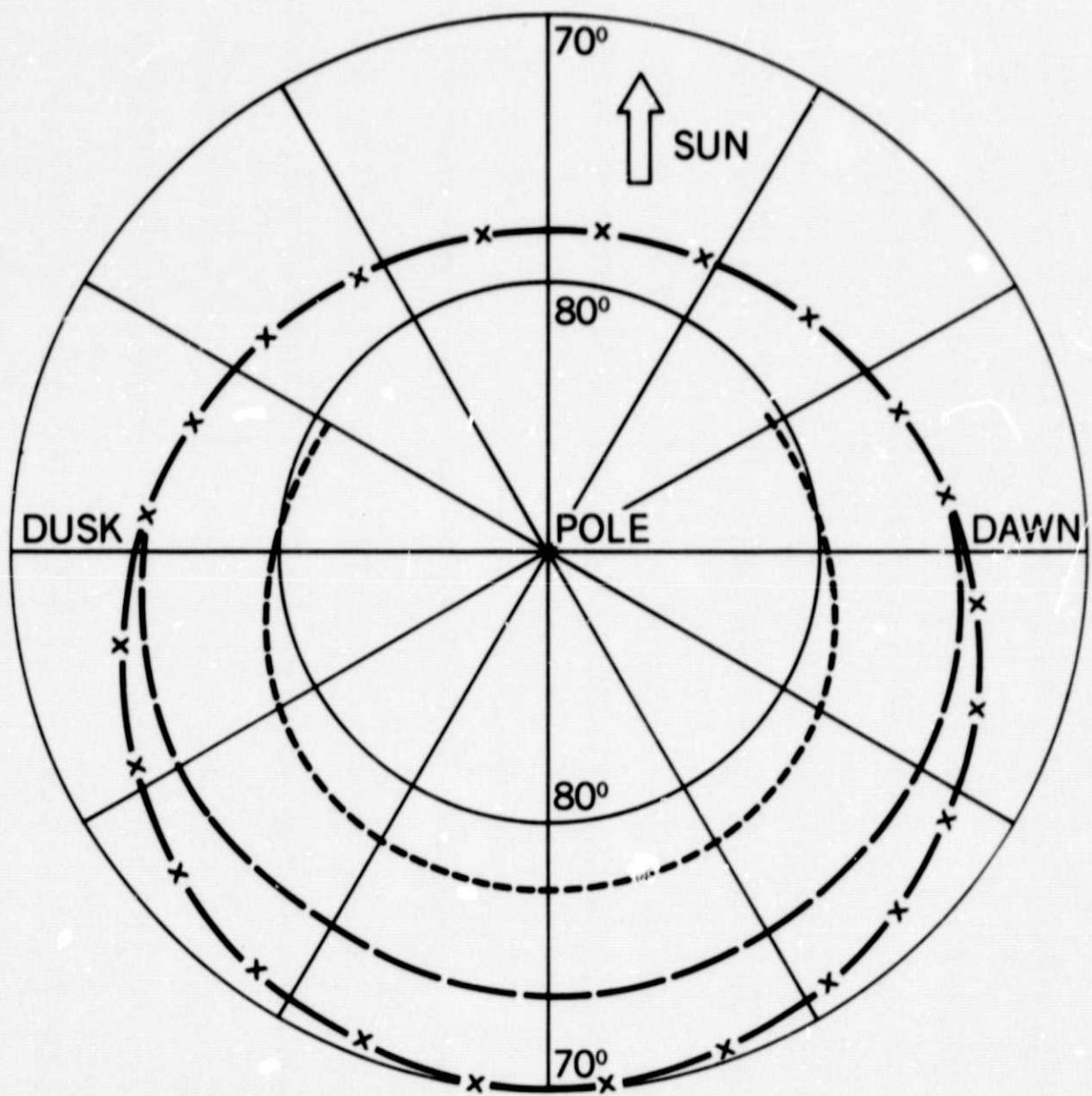


Figure 2



- x--x-- BOUNDARY OF MODEL POLAR CAP**
- — FIELD LINES CUTTING TAIL MID-PLANE AT $18.5 R_E$
(AKASOFU et al. JGR 78, 7527, '73)**
- BOUNDARY OF PLASMA SHEET AT $18.5 R_E$
(LOC. CIT. AND ALSO LASSEN, JGR 79, 3857, '74)**

Figure 3

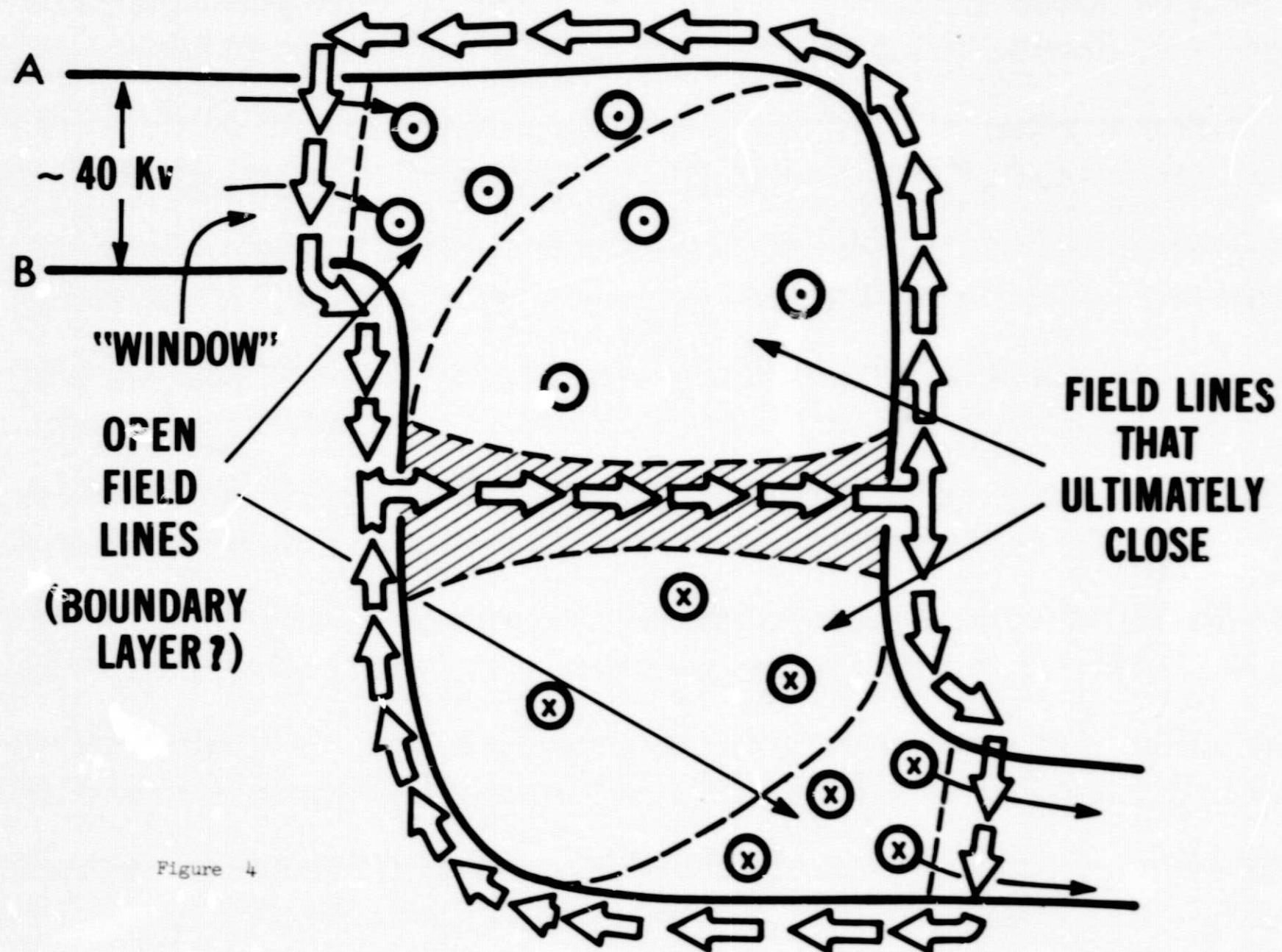


Figure 4

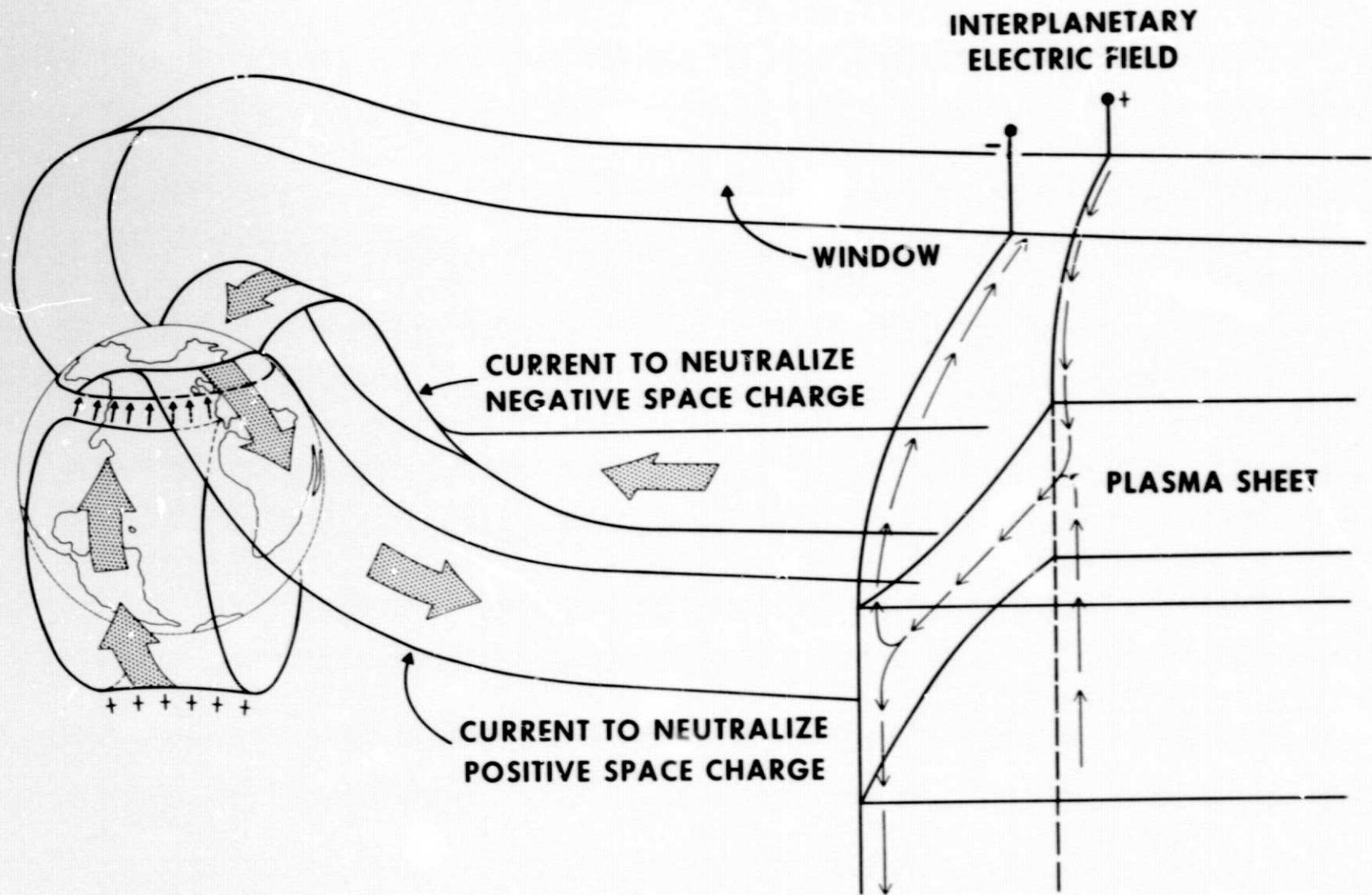


Figure 5